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ORIGINAL PAPER

Digital Photogrammetry for Documentation of Maritime Heritage

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Abstract Documentation of maritime heritage is essential for its protection, and for reference in restoration and renovation processes. These functions become problematic in the case of historical ships and boats that lack lines drawings. The purpose of this paper is to describe a procedure for creation of lines drawings based on the shape analysis of surviving historical boats or their small-scale models with the help of reverse engineering (RE) techniques. The paper describes how digital photogrammetry and the iterative method were used to analyze the shape of three historical boats: *Tomahawk*, *Refola* and *Nada.* The application of the proposed procedure produced the lines drawings of the boats as its result. The accuracy of the 3D CAD model obtained with the photogrammetric technique was verified by comparing it against a more accurate 3D model produced with the help of a RE laser scanner. The examination of the resulting lines drawings proves that the digital photogrammetry process and the proposed iterative method are adequate tools for developing lines plans of boat models. The research offers the methodological basis for the creation of an archive of lines drawings of historical boats. Such an archive would provide reference for philologically correct restorations, and permit definition and classification of distinctive elements of various types of historical boats, particularly those produced in the Campania Region.

Keywords Digital photogrammetry · Reverse engineering · Laser scanning · 3D CAD models · Philological reconstruction · Maritime heritage documentation

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Introduction

The sources of interest in the study of boats built in the past century vary based on circumstances. However, despite the difference in motivation, the interest in history of Mediterranean area maritime activities has seen as much growth in the past years, as that of northern Europe and North America. The history of maritime activities in the Campania Region (Italy) appears to be particularly fruitful for exploration, because it expands from the ancient world to the contemporary age, developing practically uninterrupted during the Middle Ages and the Modern era (Stefanile 2012a, b).

The rich maritime tradition of the region is exemplified by the well-established capability in producing boats and ships of various sizes. The large vessel construction was bolstered by the shipyard industry and by affirmed schools of naval culture (e.g., the oldest European institute of navigation and one of the three Italian universities of Naval Engineering are both located in Naples). These institutions produced a considerable amount of documents that describe the technical and morphological characteristics of large vessels built on site.

By contrast, no records were kept for smaller vessels. There are no original documents that objectively describe the hull shape or the structural features of the hulls. Instead, the technique applied then (and in some cases, still applied nowadays) was based on the use of particular templates, known as *garbo* or *mezzo-garbo* (Castro 1998), which allowed to predetermine the hull shape fairly accurately and consistently, without having to produce drawings.

In the absence of lines plans and structural drawings reliably representing various types of small boats, one resorts to physical artifacts. Unfortunately, the only evidence found today is a number of small-scale models and very few surviving boats, often in bad condition, obviously aged and deformed. This cultural environment represents an area of great interest and potential for research.

The purpose of this paper is to propose a procedure for obtaining lines plan drawings of historical boats through 3D data acquisition and digital analysis of surviving boats or their small-scale models. The lines plans can be used to carry out philologically correct restoration and to lay the basis for the creation of an archive that would allow classifying and scientifically defining distinctive elements of various types of boats.

Digital Photogrammetry in Naval Field

The problem of reconstructing the shape of even most complex objects is now solved with the use of reverse engineering (RE) systems. Today the basic principles of the RE systems are codified in complete sets of procedures, specific to various applications (Broggiato et al. 2002; Martorelli et al. 2002; Koelman 2010; Astarita et al. 2004; Martorelli and Speranza 2012; Giordano et al. 2012a, b; Martorelli and Ausiello 2012; Franciosa and Martorelli 2012; Ausiello et al. 2011a, b, 2012; Martorelli et al. 2013; Martorelli 2010; Ingrassia et al. 2013; Nalbone et al. 2013).

The digital photogrammetric technique was chosen for this research.

The desire to acquire the shape of an object using optical means goes back to the early days of photography. Over a century later, the introduction of appropriate computer software brought back the interest in the process of form acquisition through a camera, known as photogrammetry (Atkinson 2001; Egels and Kasser 2001; Kraus 2000; Selvini and Guazzetti 2000; Cheng et al. 2005; Yastikli 2007).

The photogrammetric technique is particularly adaptable to naval field application (Ahmed et al. 2012; Goldan and Kroon 2003). In fact, unlike in other types of application, in shipyard measurements the tolerances are much less restrictive, and accuracy obtained is sufficient.

The photogrammetric technique is characterized by the following phases:

- analysis of the shape of the object to be reconstructed in digital form and planning of the photographs to be taken;
- calibration of the camera;
- processing of the photos with specific software to generate a point cloud;
- transfer of the point cloud to CAD software to create a 3D CAD model.

The digital photogrammetry technique owes its great potential to two advantageous factors: the simplicity of acquiring photos for the point cloud, and low costs, mainly related to the purchase of a digital camera and software.

Materials and Methods

Three case studies were analyzed in this paper. Digital photogrammetry and iterative method were used for 3D data acquisition and surface reconstruction of three historical boats: *Tomahawk*, *Refola* and *Nada.*

Then a triangulation based 3D laser scanner was used to acquire more accurate 3D models of the boats. A comparison was carried out to evaluate the accuracy of 3D models obtained with the photogrammetric method against those obtained with the laser scanner.

Iterative Method

The method followed to obtain the final surface is divided into six phases.

The first phase consists of creating a plane functioning as the plane of symmetry (Diametral Plane). In fact, regardless of whether taken from a scale-model or a full-size boat, the initial surface (surface obtained from the point cloud generated by the RE system) must be defined in reference to an ideal plane, which will act as the plane of symmetry.

The laying of the plane is by nature a subjective choice, and is the first approximation dependent on the sensitivity acquired by the philologist. Basically, it requires evaluating the minimum planking thickness of the original hull and, in terms of the “overall geometry”, the level of symmetry of the hull. In other words, possible deformations of the craft must be evaluated and the error must be corrected by placing the Diametral Plane close to the barycenter of the sheaf consisting of all the planes that are considered a plane of symmetry for at least one point of the measured surface. The operation, due to its complexity, is reduced to the “intuitive” positioning described above.

The second phase consists of creating a horizontal plane (parallel to the designated waterline). Even for the horizontal plane, the laying is often guided by personal criteria. In some cases, reliable information comes from distinguishable signs on the hull (e.g., traces of marine vegetation or the line of the antifouling paint). Other times, it is quite sure that the horizontal plane is parallel to the Keel Line (in this case Keel and Base lines coincide). However, occasionally the information necessary to determine the sought laying of the plane is lacking, making it quite difficult to choose the plane correctly. An error in determining the horizontal plane (and therefore, the water plane) has a potential of causing grave miscalculations, because it alters the shape of the hull as perceived by the water and, consequently, modifies its hydrostatic and hydrodynamic features.

In the third phase, the transverse plane is created. The laying of the third main plane is unambiguously determined by the laying of the first two planes. The position where the plane is laid has no substantial influence on the quality of the work. It is conventionally positioned near one of the ends of the hull (generally close to the rudder or at the stern end of the water line).

In the fourth phase, the lines plan of the acquired hull can be drawn.

The fifth phase calls for analysis and corrections of the curves obtained by the sectioning of the initial surface. These corrections are requisite for accomplishing the purpose of this research—the reconstruction of the reference surface (i.e., the final surface defining the geometric features of the hull) in a manner consistent with the philological analysis carried out. It is recommended to start with the corrections of the curves considered to be richer in information and more significant in conditioning the shape (typically, those having a smaller bending radius, e.g. the cross-sections), and then pass over to other curves (the horizontal and vertical ones). Next, a first layout of the enveloping surface is drawn, and a new cycle begins: correction → layout of the surface → sectioning of the surface → new correction, and so on. The cycle is repeated until the final surface is obtained.

Once the section analysis and correction phase is complete, the sixth and last phase is dedicated to defining the final lines plan drawings.

Case Study 1: *Tomahawk*

The first case study concerns the 1:20 scale model of the *Tomahawk*, a 12 m S.I. class sailing boat. The real boat, designed in 1938 and built in 1939, is 12.2 meters long and 3.72 meters wide.

After the camera calibration, markers were positioned on the model to assist with the acquisition of the point cloud of the model surface. The markers were positioned mainly along the cross sections that are considered to be more significant and along the water line (Fig. 1a).

Five photographs were processed digitally. A point cloud (1,688 points) was constructed using the photogrammetric technique, and the final 3D model was obtained in a CAD environment (Fig. 1b).

The timing of each step is shown in Table 1.

The above-described iterative method was applied for the analysis of the 3D model. The cycle (correction, surface layout, sectioning, further correction) was repeated, until the final surface was obtained.

Figure 2 shows a comparison between the initial curves (in black) and the corrected ones. The final result of the process—the lines drawing of the boat—is shown in Fig. 3.

Case Study 2: *Refola*

The second case concerns *Refola* (Fig. 4). *Refola* is a *Lanzino*, which is a historical type of boat that was used starting the end of the XIX century to transport people and light goods from Bagnoli (a district in Naples) to the nearby island of Nisida. During the XX century the *Lanzino Class* was created based on this type of boat. The *Lanzino Class* is a restriction class; its main dimensions are: 4.6 m (hull length), 1.74 mm (beam) and 10.5 m (mast height).

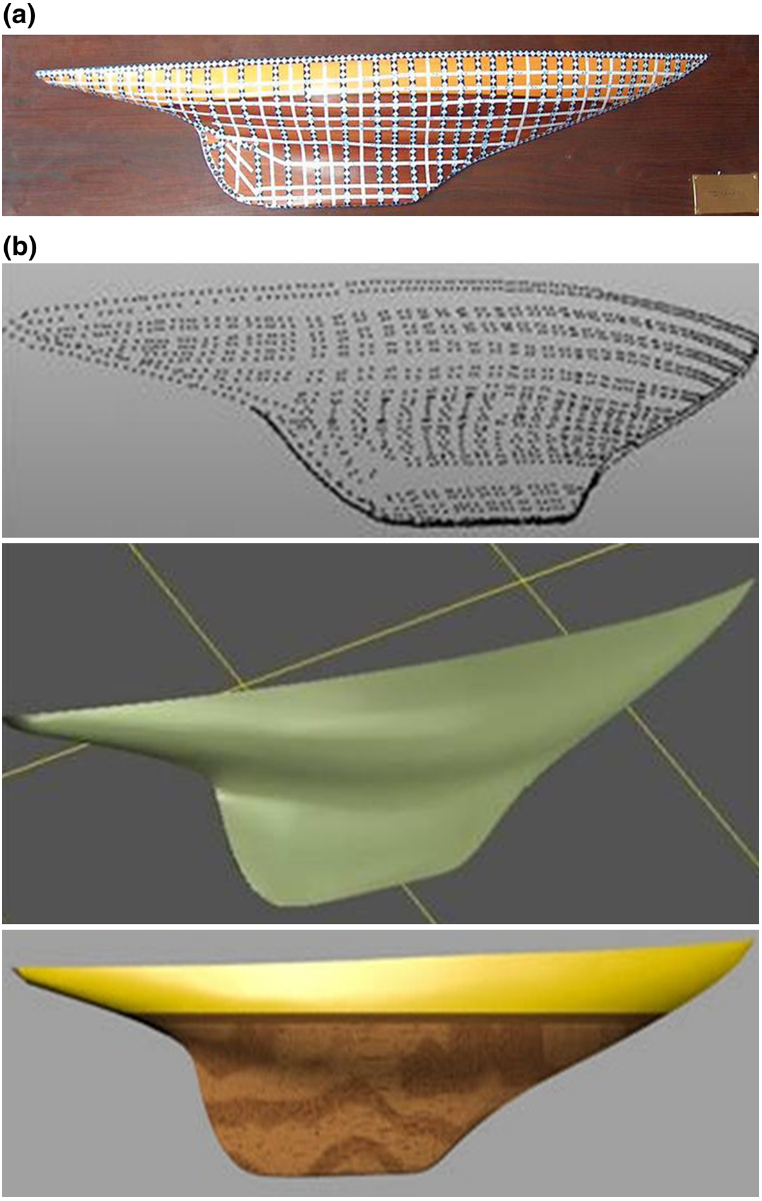


Fig. 1 *Tomahawk*: from the physical object to 3D CAD model. **a** 1:20 scale model of the 12-m class *Tomahawk*. **b** 3D CAD model obtained starting from the points cloud (1,688 points) acquired by photogrammetry

Markers were positioned on the model to assist with the acquisition of the point cloud of the model surface, mainly along the cross sections and the water line (Fig. 5).

Eighteen photographs were processed digitally. A point cloud was constructed using the photogrammetric technique, and the final 3D model was obtained in a CAD environment (Fig. 6).

Table 1 Steps and time required

Steps	Time required (min)
Preparing the markers	30
Applying the markers	30
Taking photos	10
Removing the markers	10

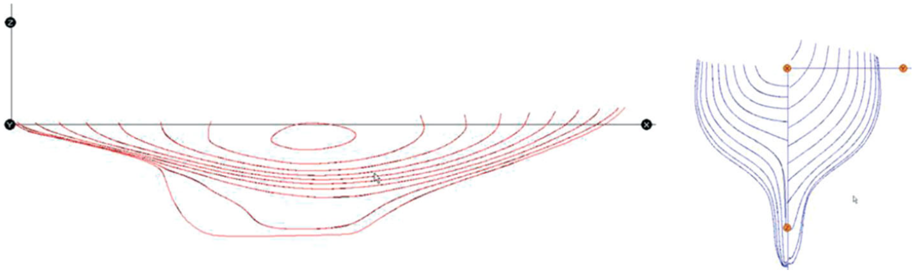


Fig. 2 Comparison between the initial curves and the corrected ones

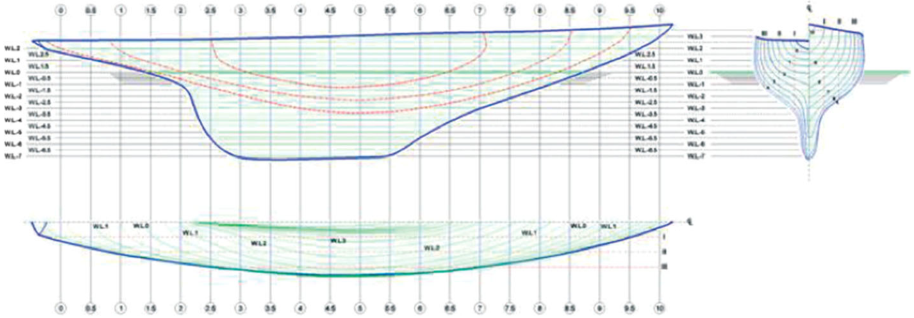


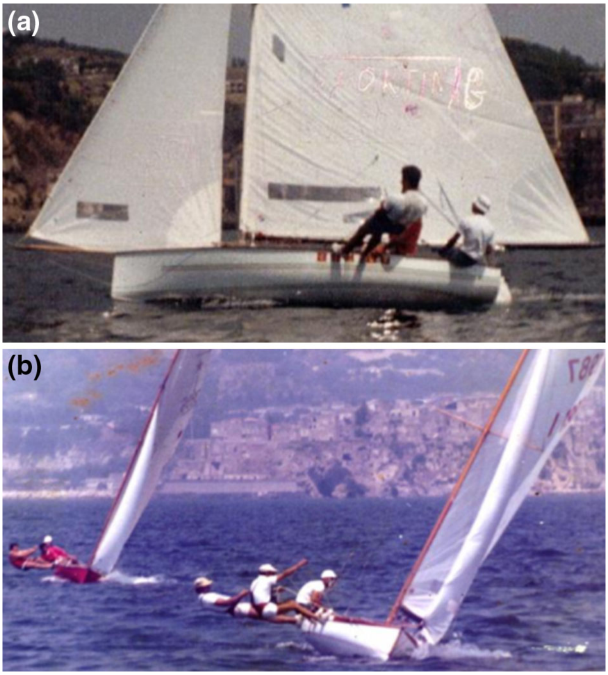
Fig. 3 Final lines drawing

Figure 7 shows the final lines drawing of *Refola* obtained by applying the above-described iterative method (Table 2).

Case Study 3: *Nada*

The third case concerns *Nada*, a sailing boat built in 1897. *Nada* was designed as a 10.5 m International Tonnage boat, and later underwent a series of modifications. The modifications to the stern and deck elevated the deck level by approximately 30 cm, and evidently modified its shape in comparison to the original design (Fig. 8).

Fig. 4 *Refola*



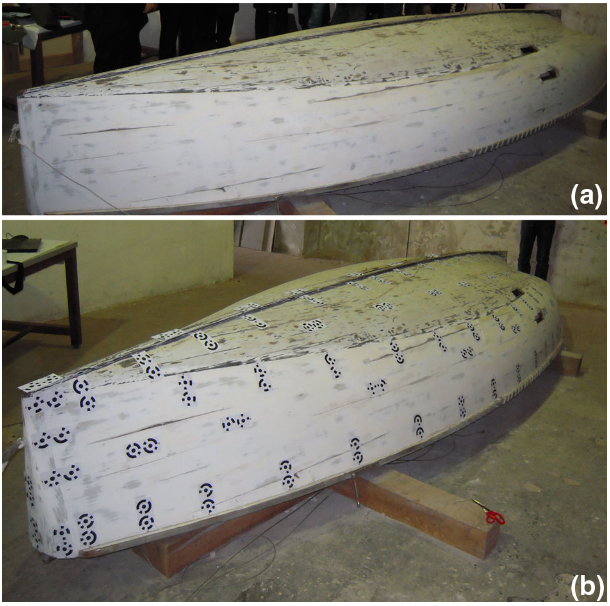


Fig. 5 Positioning of the markers on *Refola*

Markers were positioned on the model to assist with the acquisition of the point cloud of *Nada* surface (Fig. 9a). This operation took 90 min, due to the difficulty in reaching the higher areas of the hull, rising about 3 meters from the ground (Fig. 8).

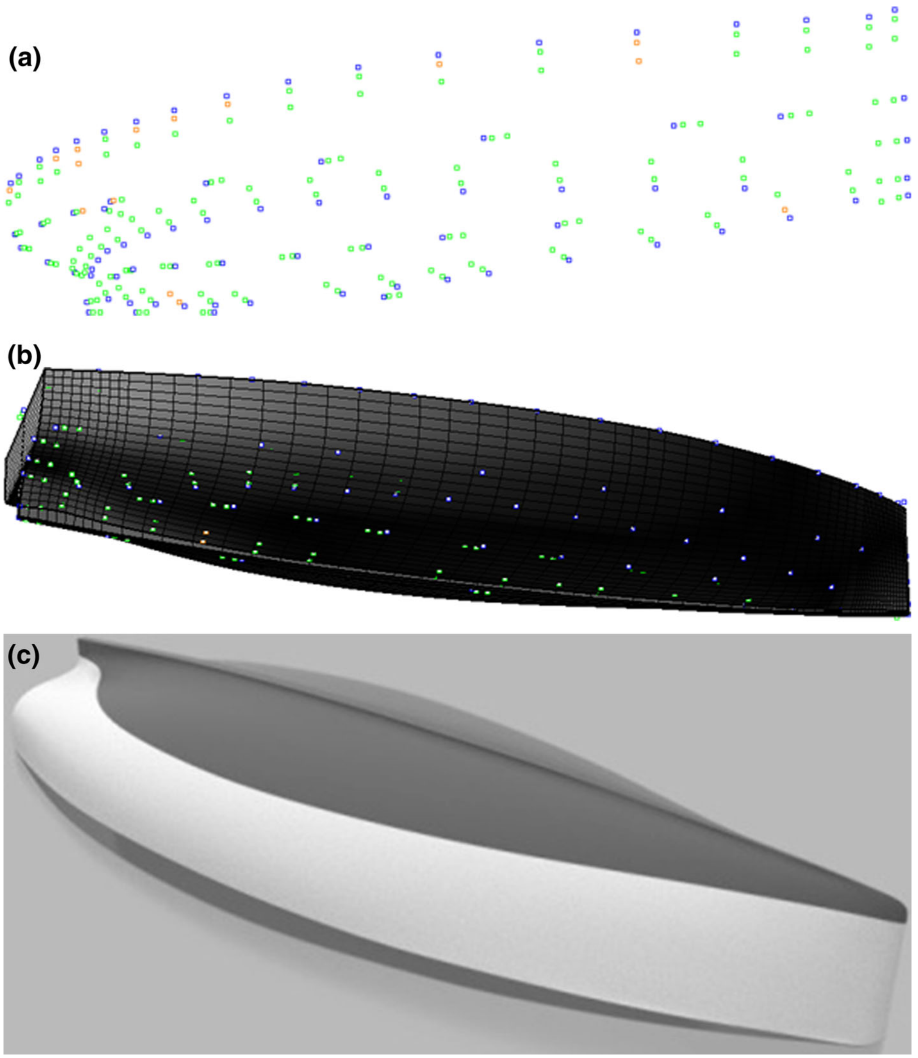


Fig. 6 3D CAD model obtained starting from the points cloud acquired by photogrammetry

The most favorable photo angles were selected, so as to allow for the best light conditions, and to protect the camera lens from direct sunlight at the same time. Shortage of space around the ship did not allow for photographs of the entire hull. However, it did not compromise the final result of the photogrammetric process, since the 3D model reconstruction is meant to be a strictly symmetrical idealistic representation of the ship. The only drawback was our inability to use less photographs for the project.

Altogether, the survey took 2 h. Ten photographs were used to construct the point cloud (2,122 points), and Geomagic Studio software was used to create a 3D CAD model (Fig. 9b).

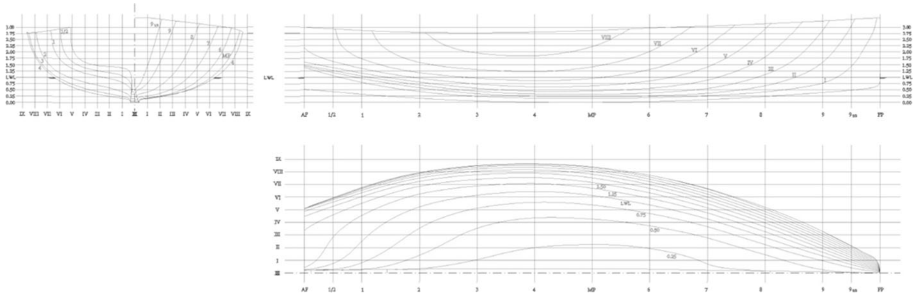


Fig. 7 Final lines drawing of *Refola*

Table 2 Characteristics of the acquisition

Konica Minolta VI—9i laser scanner	
Total scanning time	20 min
Amount of points	73,868

Fig. 8 *Nada*

Figure 9c shows the final lines plan drawing of *Nada*, obtained by applying the above-described iterative method.

Results

In order to reach a conclusion about the advisability of the use of photogrammetric technique in naval field applications, the accuracy of the measurements obtained with photogrammetry was evaluated by comparing them against a laser scanner model. The same model of Tomahawk was scanned with a Konica Minolta VI 9i system operating based on the principle of optical triangulation. The system is available at the CREA (Center of Reverse Engineering Applications) Laboratory of University of Naples Federico II.

No opacifier sprays were used, due to the high value of the boat model. However, because laser scanners are very sensitive to ambient light conditions, the lighting conditions were optimized to allow for better 3D data acquisition.

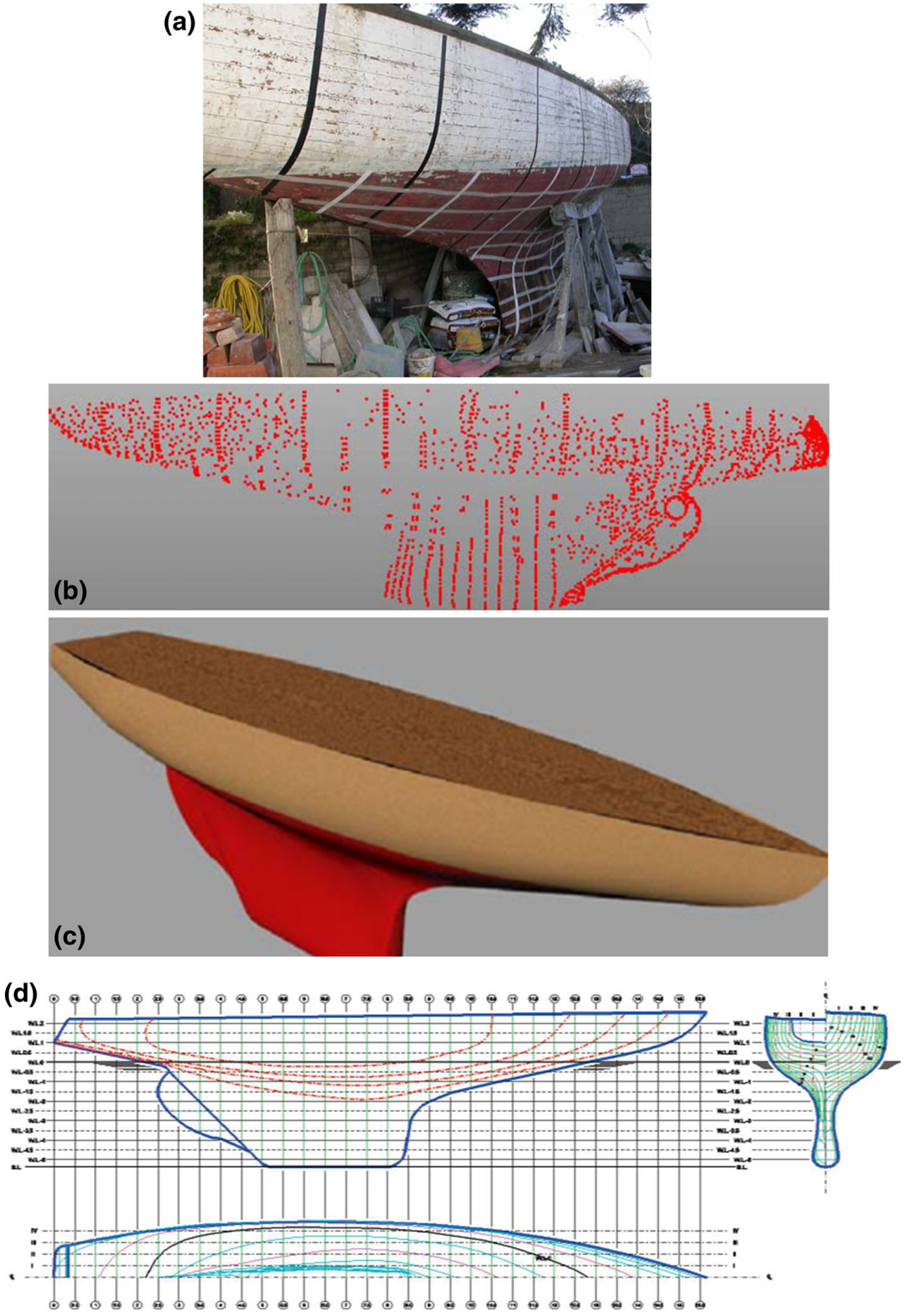


Fig. 9 *Nada*: from the physical object to final lines drawing. **a** Positioning of the markers on *Nada*. **b** Points cloud and CAD model of *Nada*. **c** Final lines drawing of *Nada*

Geomagic software was used to reproduce the surfaces of the vessel from the obtained point cloud. Once the laser scanner model was reconstructed, it was possible to compare it with the point cloud acquired with the photogrammetric technique.

The model surface was aligned with the point cloud, and the analysis of deviations was performed. The results illustrated in Fig. 10 show an average deviation of 1.25 mm, based on Eucledian method.

Discussion

In our research we faced a few difficulties pertaining to surface reconstruction, data analysis and technological limitations.

In surveying of ancient ships, two fundamental objectives must be addressed. On one hand, there is a need to reproduce a virtual model of the historical boat in the exact present state; on the other hand—a need to reproduce the hull in a form consistent with canonical Naval Architecture, suitable for a correct evaluation both of the behavior of the boat and the complexity of the construction. In practice, however, the design of the keel obviously precedes the production of the hull. The graphical reproduction, therefore, has all the features of an idealistic representation: the curves are absolutely fluent, the surface has a smooth flow without any unforeseen interruption, and the shape is strictly symmetrical (except in special cases). By contrast, a real object in general, and an old hull or an old model in particular, are characterized both by inaccuracies due to manufacturing errors, and by deformation due to common wear and aging.

The difficulty inherent in analyzing the data obtained from the survey with RE is that it has a great number of potential uses in various areas of philological research. For example, it may be important for the research to highlight the level of accuracy reachable (or reached) by skilled workers at a certain time and place. Or it may be crucial to single out a certain type of the paradigmatic shape by comparing the data obtained from different surveys and identifying the common characteristic elements. It follows that the filtering criteria used to include or exclude the deviations in shape will be different, depending on the main purpose of the project.

Similar to the examples above, in this research we had to determine, which deviations in the curves of the hull surface to attribute to the construction techniques used or to the characteristics of the models (*Refola*, *Tomahawk*, *Nada*), and which deviations came from the wear and aging.

We observed both advantages and disadvantages while using laser-scanning systems.

The comparison against the more accurate laser system demonstrated that the proposed procedure, as previously mentioned (Goldan and Kroon 2003; Gerbino et al. 2004; Lightfoot et al. 2007), is suitable to be used for preserving and restoring traditional ships as historical evidence or for perpetuating traditional skills.

However, in field conditions the use of optical systems based on the projection of light on an object to acquire its reflection by a sensor, typically a CCD, such as laser or fringe projecting systems, has some limits. In fact, these systems are very sensitive to environmental conditions (light, distance from the object, color of the object, etc.), often making geometry acquisition very difficult, and requiring complicated operations to correct the acquired data.

In addition, in the naval field as well as in other industrial contexts, it is often difficult to simply reach the object with survey instruments, and even supplying power to the scanner can sometimes become a big problem.

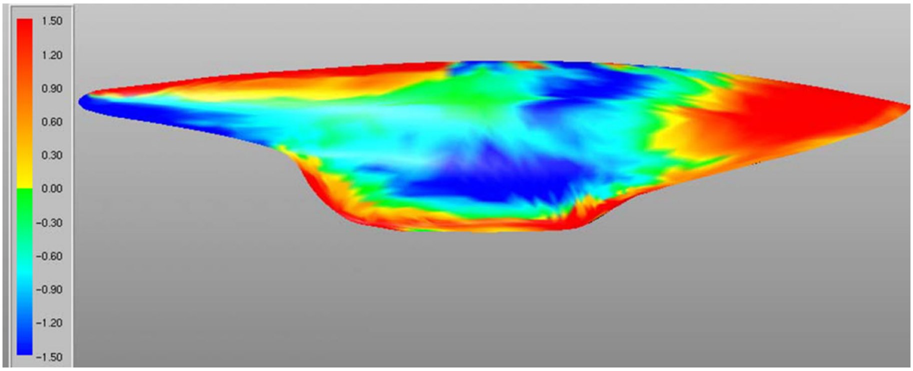


Fig. 10 *Tomahawk*: comparison laser surface—photogrammetric points cloud

These limits are overcome by using photogrammetry (Ahmed et al. 2012).

Conclusions and Future Developments

In the paper, we described a procedure that details the creation of lines plan drawings of historical boats; the plans are useful for many purposes: for example, for restoration.

It is very important that we quickly survey as many boats as possible, both full-size and small-scale, before they physically disappear. Digital photogrammetry is used as the leading technique in this procedure. The paper shows that, although the photogrammetric technique is less accurate than the RE laser systems, it is quick and inexpensive, and is useful in acquiring line plans of other historical boats.

The findings will allow the creation of an archive of lines plans of existing boats. The purpose of such an archive is to define and classify distinctive elements of different types of historical boats, particularly those produced in Campania Region: *Lancia*, *Gozzo*, *Feluca*, *Tartana*, *Paranza*, *Lanzino*, etc.

The classification of the main features of historical boats based on the hull shape and structural geometry yields remarkable applications. It provides reference materials for philologically correct restorations of the most valuable existing boats, as well as a possibility of the creation of a virtual naval museum—a unique opportunity.

Lastly, the findings of performed surveys enable the study of technological evolution and cultural influences determined by the migration of seafarers.

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